ENERGY-EFFICIENT TDMA FOR SENSOR FUSION [1]

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ABSTRACT

We consider the problem of minimizing the energy needed for data fusion in a large scale sensor network by varying the transmission times assigned to different sensor nodes. The optimal scheduling protocol is derived, based on which, we develop a low-complexity inverse-log scheduling algorithm that achieves near-optimal energy efficiency. To eliminate the communication overhead required by centralized scheduling protocols, we also develop a distributed inverse-log protocol that is applicable to networks with a large number of nodes. Simulations demonstrate that this distributed scheduling protocol achieves substantial energy savings over uniform time division multiple access protocol.

1. INTRODUCTION

A wireless sensor network typically consists of a large number of sensor nodes distributed over a certain region. Each node monitors its surrounding area, gathers application-specific information, and transmits the collected data to a "master" node (a.k.a. fusion center or gateway). A sensor node may need to operate for years relying on a tiny battery. It is therefore important to optimize the energy efficiency of all sensor operations, which include sensing, computation and communication.

It is known that the energy required to transmit a certain amount of information is exponential to the inverse of the transmission time [Berry and Gallager, 2002]. This power-delay tradeoff principle has been applied to the design of energy-efficient packet scheduling protocols for multiuser communication networks [El Gamal et al., 2002], where an iterative MoveRight algorithm was proposed and was shown to converge to the optimal schedule.

The MoveRight algorithm however, is extremely complicated and requires knowledge of all users' channels as well as their queue lengths. In this paper, we will develop optimal and suboptimal *centralized* scheduling protocols that have much lower computational complexity. To avoid the communication bandwidth and power overhead required by centralized protocols, we will also design a *distributed* scheduling protocol, in which each sensor needs only to know its own channel and queue length. We will demonstrate that this distributed protocol performs very closely to the optimal scheduling in large-scale networks.

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2. PROBLEM FORMULATION

Suppose a fusion center needs to collect information from N sensors within the time interval $[0, T]$. We assume that the nth sensor has a data sequence of B_n bits to transmit, the channel between it and the fusion center is flat fading with constant coefficient h_n over $[0, T]$, and the noise is additive white Gaussian.

Supposing without loss of generality that the communication channel bandwidth is 1, and a time interval of T_n is assigned to sensor n, then the minimum transmission power P_n needed to transmit B_n bits within this interval is determined by the channel capacity:

$$T_n \log_2 \left(1 + \frac{P_n |h_n|^2}{N_0} \right) = B_n, \tag{1}$$

where N_0 is the noise power spectral density. The energy consumption (normalized by the noise power) of the nth node is therefore

$$E_n := \frac{P_n T_n}{N_0} = \frac{T_n}{|h_n|^2} \left(2^{\frac{B_n}{T_n}} - 1 \right). \tag{2}$$

Our objective is to find a set of time allocations $\{T_n\}_{n=1}^N$ for all N sensors, such that the total energy consumption over $T = \sum_{n=1}^N T_n$ is minimized.

3. ENERGY-EFFICIENT PROTOCOLS

3.1 Optimal Scheduling.

The optimal schedule can be obtained using Lagrange's multiplier method:

$$\frac{1}{|h_n|^2} 2^{\frac{B_n}{T_n}} \left(1 - \frac{B_n}{T_n} \log_e 2 \right) = \lambda, \quad n = 1, \ldots, N, \tag{3}$$

where λ is determined by the constraint $\sum_n T_n = T$.

In Fig. 1, we plot (in dB) the energy gain of the optimal scheduling over uniform TDMA ($T_1 = \cdots = T_N$) for networks of 100 and 10 sensors, respectively. In this simulation, we assume that $B_1 = \cdots = B_N$. We observe that compared

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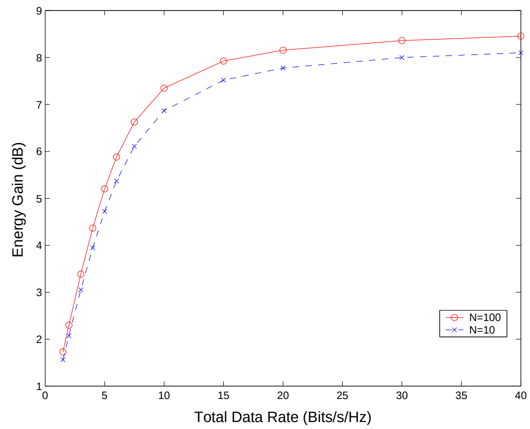

Fig. 1. Energy gain of optimal scheduling

with the uniform TDMA, the optimal scheduling reduces the total energy consumption by more than 8dB at high data rates. When the total data rate is less than 1bits/s/Hz, the energy saved by optimal scheduling is insignificant, but it increases quickly as the demand on the total data rate increases.

3.2 Inverse-log Scheduling with Clipping.

Focusing on the case of large B/T where the potential for power savings is largest, we derive the following low-complexity algorithm:

$$T_n = \begin{cases} T'_n & 0 < T'_n \leq \frac{B_n}{B} K_\alpha T \\ \frac{B_n}{B} K_\alpha T & \text{otherwise} \end{cases}, \tag{4}$$

where $T'_n := \frac{B_n}{\log_2(\lambda |h_n|^2)}$ and $K_\alpha > 1$ is a predetermined clipping threshold.

3.3 Distributed Inverse-log Scheduling.

To eliminate the bandwidth and power overhead required by the above two centralized protocols, we develop an adaptive distributed scheduling protocol for large-scale sensor networks (details can be found in the journal version).

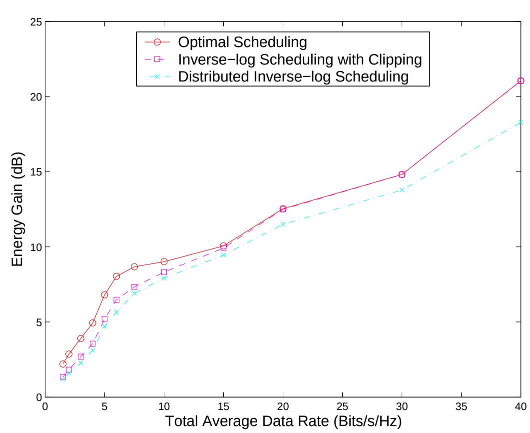

Fig. 2. Performance of the distributed scheduling algorithm with Poisson-distributed queue lengths ($N = 100$)

In Fig. 2, we simulate a network with $N = 100$ sensors. The channel fading is assumed to be *i.i.d.* Rayleigh, and the amount of data in each sensor's buffer is Poisson distributed. We observe that the proposed scheduling algorithms achieve energy gain as much as 20dB over traditional TDMA, which corresponds to 99% energy savings. The simple distributed inverse-log protocol, which requires only local queue and channel information, achieves close-to-optimal energy efficiency.

4. PERFORMANCE ANALYSIS

Proposition 1: *Assume that i) the channels between the sensors and the fusion center experience* i.i.d. *Nakagami-m fading; and ii) the amount of backlogged data at each sensor is Gaussian distributed ($NB_n/T \sim \mathcal{N}(\bar{B}/T, \sigma_B^2)$). With $\psi(m)$ denoting the Digamma function, the asymptotic (for large $\bar{B}/T$ and N) energy gain of the inverse-log scheduling with clipping over traditional TDMA is*

$$G := \frac{E_{tot}^{(u)}}{E_{tot}} = \frac{e^{\psi(m)}}{m-1} 2^{\frac{\log_e 2}{2}\sigma_B^2}. \tag{5}$$

Proposition 1 explains the behavior of the energy gain of the proposed scheduling protocols at high data rate in Fig. 2. In obtaining Fig. 2, we have assumed that B_n is Poisson distributed, which means that σ_B^2 increases linearly as $\bar{B}$ increases. Since the Poisson distribution can be approximated by a Gaussian when its mean is large, (5) predicts that at high data rates, the energy gain should grow linearly (in dB) as the average data rate increases. We confirm from Fig. 2 that this prediction fits the simulation well.

5. CONCLUSIONS

We developed centralized and de-centralized energy-efficient scheduling protocols for sensor fusion. By assigning longer transmission times to sensors experiencing worse channel conditions, we significantly improve the energy efficiency of the data fusion operation. To analyze the energy consumption performance of the inverse-log algorithm, we computed its asymptotic energy gain over traditional TDMA. We showed that the energy gain of the proposed approach increases as the channel variations among different sensor nodes increase. When the total data rate of a network is high, the energy gain does not depend on the total data rate, but increases as the variation among different nodes' queue lengths becomes larger.

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